

Lubrication Lab Call



Lubricant Effects on Combustion and Emissions Control

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Project FT049

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F&L LUBRICATION LAB CALL - LUBRICANT TECHNOLOGY - *INNOVATION, DISCOVERY, DESIGN, AND ENGINEERING*



Three Thrust Areas, 4 National Labs, Multiple Industrial Partners
Lab Call Project Support for FY17 - \$3M @ 75%

- Thrust I - Surface and Lubricant Interactions
 - ANL, ORNL

- Thrust II - Technology Innovation, Design & Synthesis
 - PNNL, ANL, ORNL

- Thrust III - Lubricant Effects on Combustion, Emissions Control and Fuel Economy
 - ORNL, NREL

OVERVIEW: THRUST III

Lubricant Effects on Combustion, Emissions Control, and Fuel Economy



Timeline

- New project that builds on previous research. Collaborative response to Lab Call for proposals.
- FY16: 4-lab team response to Lab Call
- FY17: Lubricant Additive Catalyst Effects, Lube Effects on GDI PM, Low-Speed Pre-Ignition, Vehicle-level Fuel Economy
- FY18-FY19: Continuation of 3 year project, pending budget approval

Budget

- FY17: \$1M
- Covers 4 sub-projects, 2 Labs

Barriers

- MYPP 2.4 E: *Inadequate data on long-term impact of fuel and lubricants on engines and emissions control systems*

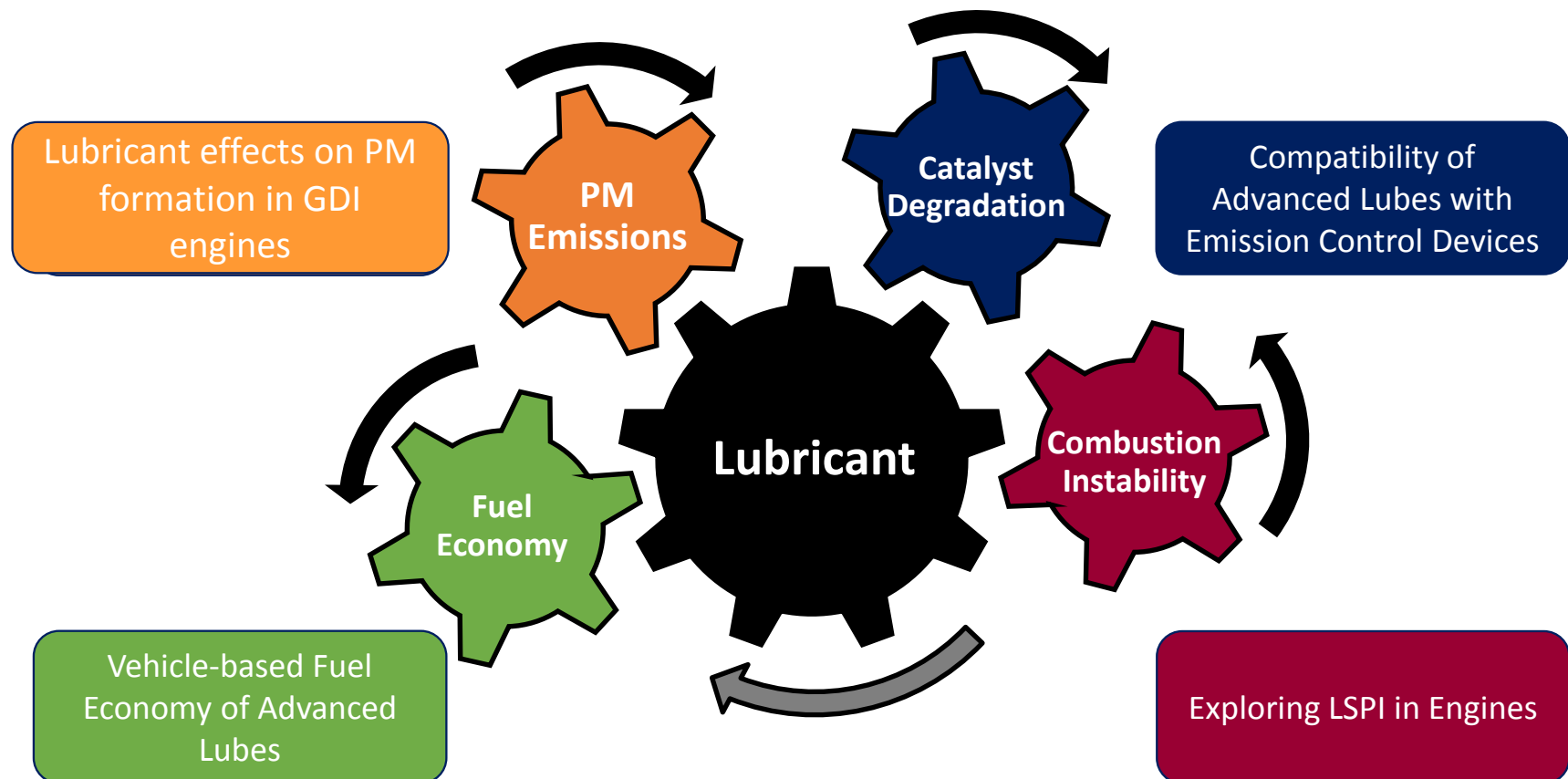
Partners

- Industry Collaborators
 - GM, Driven Racing Oil, Ford
- National Laboratories
 - ANL, NREL, ORNL, PNNL
- Academic
 - Univ. of Tennessee

RELEVANCE OF LUBRICANT PROPERTIES RESEARCH – THRUST III



- New lubricant materials unacceptable if they damage engines, catalysts
- Need to understand which properties to control for Thrust I and II research



OBJECTIVES AND RELEVANCE



Objectives

- Elucidate the impact of different lubricant properties on PM emissions and emissions control systems
- Explore/understand cause(s) of Low-Speed Pre-ignition (LSPI) including ignition properties of lubricants
- Develop vehicle-based protocol to bridge to Sequence Test; evaluate lubricants that can improve fuel economy

Relevance:

- Important to ensure new lubricant or lubricant additives developed in Thrust I and II research do not contribute to increased PM emissions or impact emissions control durability in a negative way
- Downspeeding and boosting are limited by LSPI
- Small fuel economy gain across legacy fleet can have significant impact on national fuel consumption

MILESTONES MET OR ON TRACK

(✓=COMPLETED)



- **Quantify lubricant contribution to exhaust PM during cold start**
 - Data collection on viscosity completed (✓); data analysis ongoing and on track
- **Identify catalyst effects of down-selected additives on TWC reactivity and material properties**
 - Materials from Thrust II partners at ORNL (✓), Argonne and PNNL.
- **Develop correlation between constant volume combustion chamber (CVCC) studies and engine studies of LSPI**
 - ✓ Provide up to 12 lubricants acquired for engine LSPI experiments to NREL for complementary evaluation in Ignition Quality Tester
 - Lubricant formulations complete on CVCC (✓); engine data collection ongoing
- **Complete vehicle experiments to confirm ability to measure fuel economy differences between lubricants on multiple vehicles/engine architectures**
 - ✓ 4-cylinder engine (Nissan Frontier -FY16)
 - Evaluate vehicle lubricant screening protocol using modern down-spiced GDI engine-equipped vehicle (underway with MY2016 GDI vehicle)

SUMMARY OF TECHNICAL ACCOMPLISHMENTS



- **Lubricant effects on PM formation in GDI engines**
 - Quantify lubricant contribution to PM during cold start
 - Completed cold-start experiments with 3 different viscosity oils
 - PM mass, composition, and particle size and number
- **Compatibility of Advanced Lubricants w/ Emissions Control**
 - Compared impact of Ionic Liquid (IL) additive with ZDDP on 3-way cat
- **Exploring LSPI in Engines**
 - Developed engine protocol for reproducible LSPI event clusters
 - Additive impacts being measured
- **Vehicle Fuel Economy**
 - Developed and demonstrated vehicle-based test protocol to screen lubricants for improved fuel economy
 - Completed five campaigns, 6th underway
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LUBRICANT EFFECTS ON PM FORMATION IN GDI ENGINES



Approach:

Measuring lubricant properties' effects on PM emissions during cold start

- Research tool to study cold start and hot re-start emissions and fuel consumption
- Mobile cart - Set up in Vehicle Laboratory for full-flow dilution emissions sampling (filters)
- Instrumented for cylinder pressure, crank angle, fuel flow, etc.
- Investigated lubricant effects on GDI cold start particulate matter (PM)
 - Real time PM size, number
 - Filter samples for mass, EC-OC, metals, HC species
 - 3 viscosities, 1 brand (Mobil 1®)
- 12-16 starts per day
 - Large sample size
- E10 Certification fuel



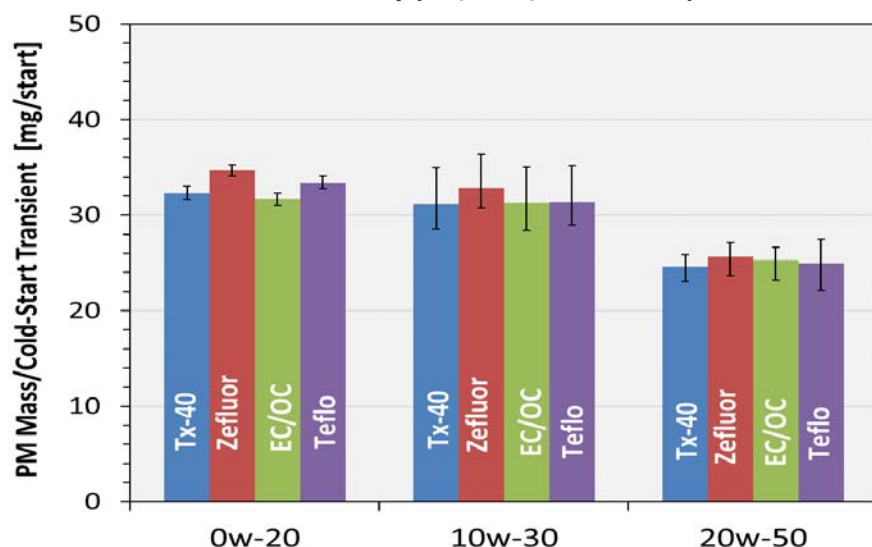
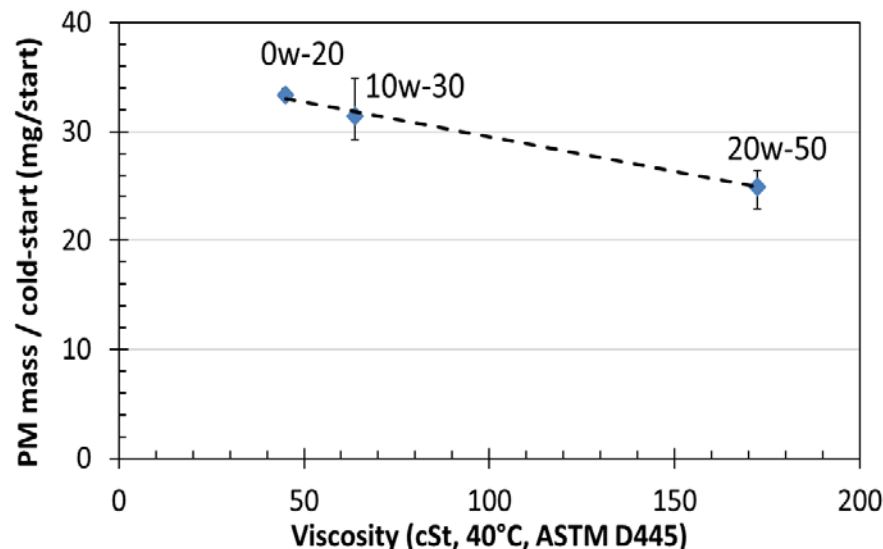
High accuracy fuel flow meter

LUBRICANT EFFECTS ON PM FORMATION IN GDI ENGINES

- LUBE VISCOSITY



Reduced viscosity lubricants result in higher cold-start PM production



- PM mass and viscosity show inverse linear correlation
- Statistical confidence in the PM mass collection, consistent across different filter medium types
- Indirect PM production from Lube or Direct PM production?

Key:

Tx-40 = PTFE-coated glass fiber

Zefluor = supported PTFE membrane

EC/OC = quartz fiber filter for elemental carbon (EC) and organic carbon (OC)

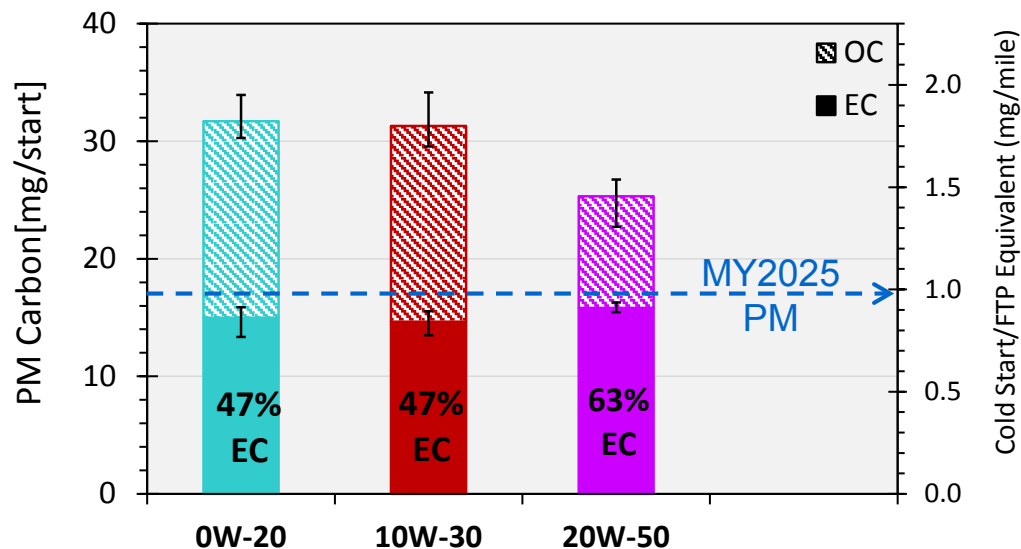
Teflo = PTFE membrane (2 μ m pore)

LUBRICANT EFFECTS ON PM FORMATION IN GDI ENGINES

- PM CHEMICAL COMPOSITION



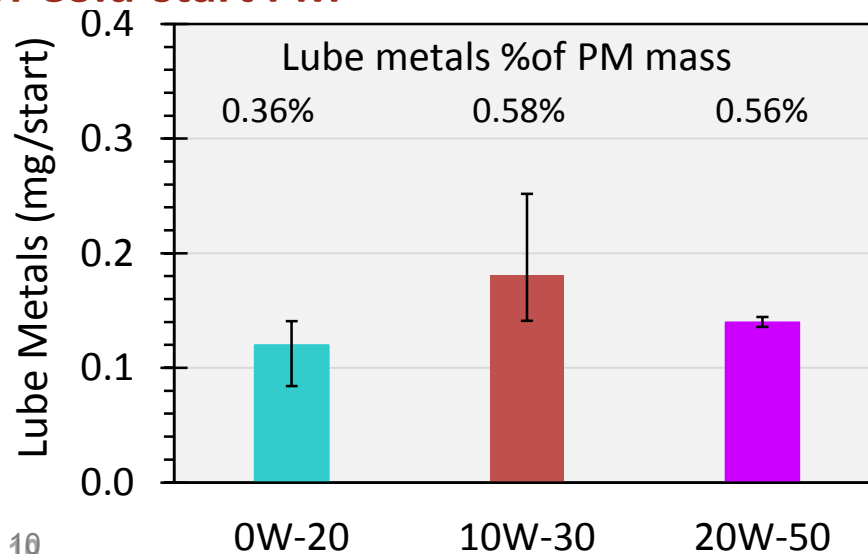
Reduced organic carbon (OC) found when using higher viscosity lubricant



- Over the FTP cycle, EC comprises > 80% of all GDI PM
- High OC may indicate Lube contribution
 - HC speciation ongoing

Metals constitute only a small fraction of Cold-start PM

- Metals measured directly on filter by XRF
- P,S,Ca,Zn \approx 90% of total
- Metals are small amount of total PM mass

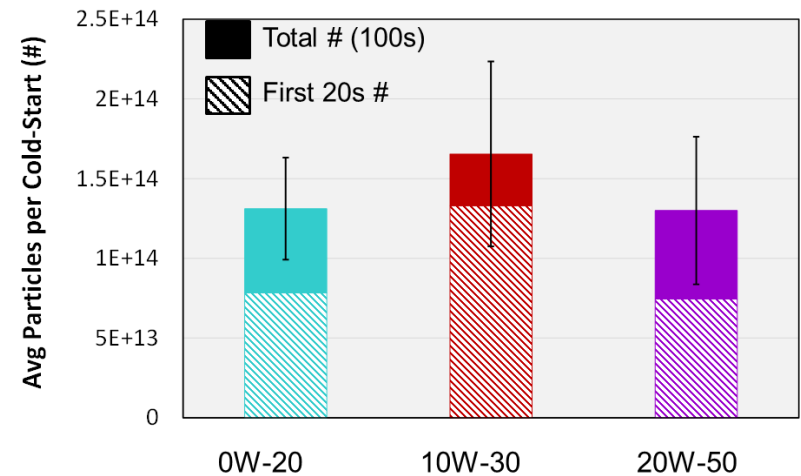
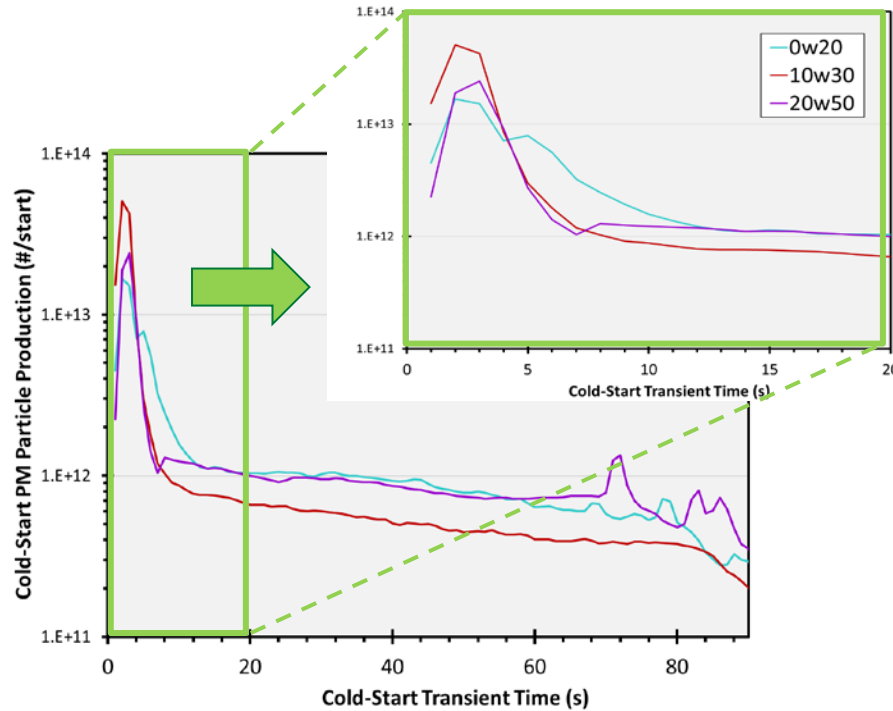


LUBRICANT EFFECTS ON PM FORMATION IN GDI ENGINES

- PM PHYSICAL PROPERTIES



Majority of PM produced in first 20s of Cold-Start transient for all lubricants



- Viscosity doesn't show much influence on number of particles (#) produced during cold-start
- First 20s generates majority of cold start particle number
- Confidence: Averages of 12 cold-starts;
error bars = 1 Std Dev

SUMMARY OF TECHNICAL ACCOMPLISHMENTS

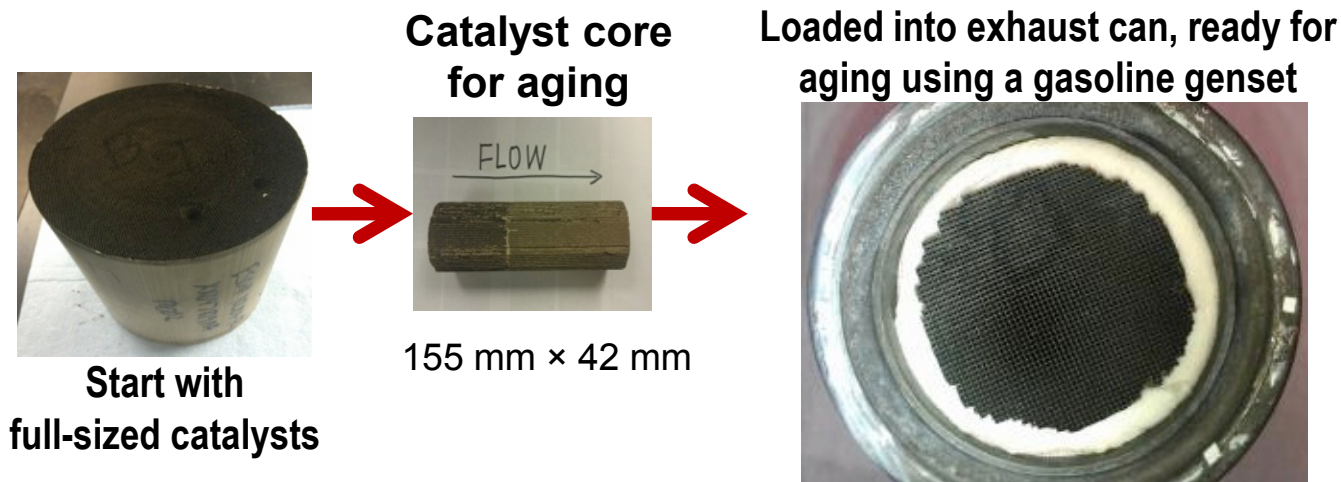


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COMPATIBILITY OF ADVANCED LUBRICANTS WITH EMISSIONS CONTROL DEVICES

Approach uses engine aging, additive in fuel

- Westerbeke stoichiometric gen-set
 - 2-cylinder, 0.35L, 4-stroke, liquid cooled, 2200 rpm, multiport EFI, oxygen sensor in exhaust
- Introduce lubricant additive into system through the fuel mixture
 - full-useful life additive content
 - “high-normal” consumer (SAE 2013-01-0884)
 - 90 mg/km or 1.8 qts/10,000 miles
 - 1%wt additive in lubricant

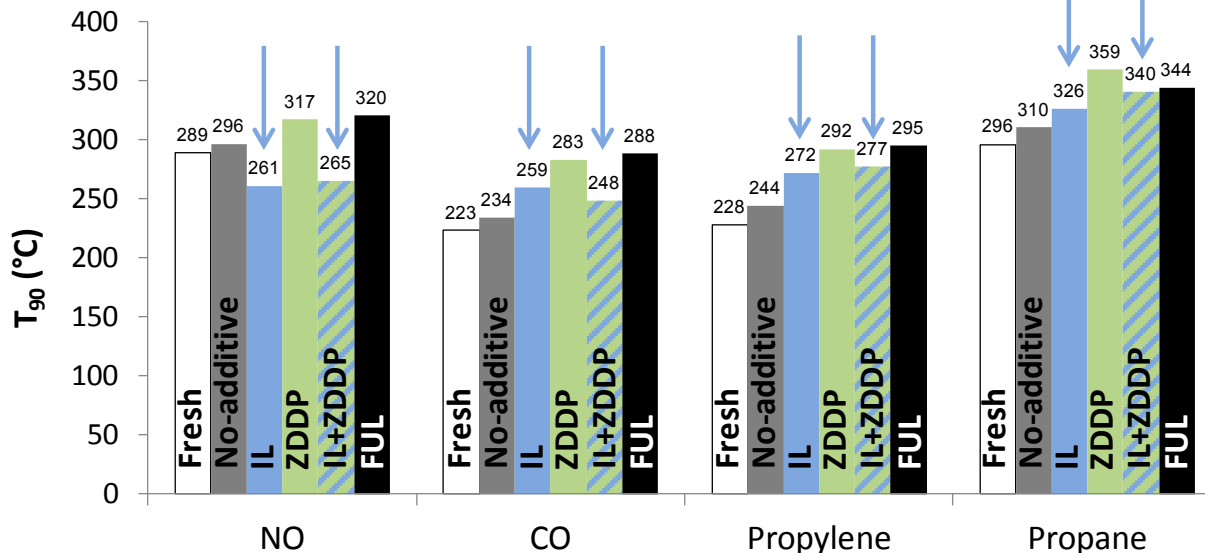


COMPATIBILITY OF ADVANCED LUBRICANTS WITH EMISSIONS CONTROL DEVICES



- TWC samples: fresh, NA, ZDDP, IL, IL+ZDDP, and road-aged; post desulfation
- Water Gas Shift (WGS) reaction sensitive to catalyst changes

IL generally has moderately less catalytic impact than ZDDP for TWC light-off behavior



Minimal impact
NA – no additive

Notable impact
IL-only
ZDDP-only
IL+ZDDP

Severe impact
RA – road aged
(FUL)

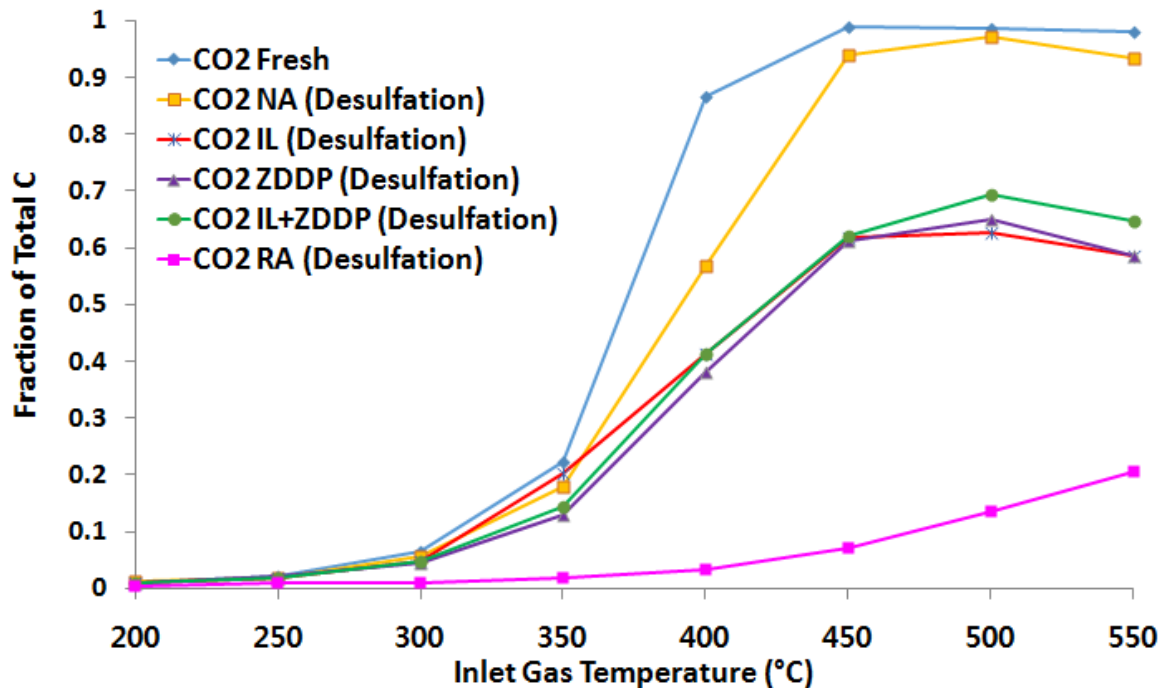
- ▶ WGS deactivation is similar for all three accelerated aged additives; IL no worse than ZDDP
- ▶ Low performance of RA sample is likely due to sintering of Pd particles (Thermal-aging)

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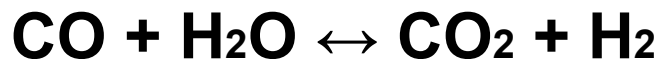
WGS Reaction (After Desulfation)



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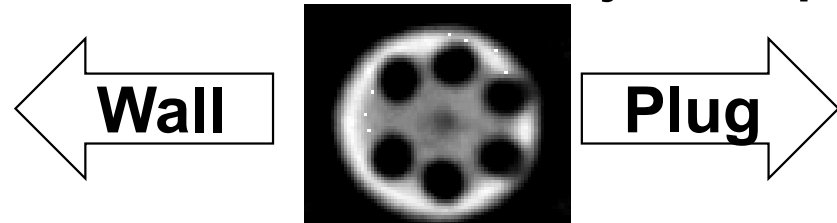
EXPLORING LSPI IN ENGINES

Approach: Enable statistical analysis of LSPI propensity due to fuel and lubricant

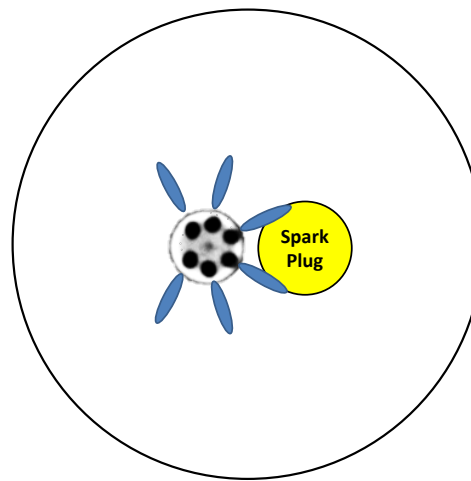


- Hardware intensive
 - Engine, pressure sensor
- Low load – High load Cycle (21 bar BMEP)
- Timing retard, $\lambda = 1.05$
- Stock GDI orientation was found to require high load conditions for SPI event occurrence
 - SPI events seem to be singular in nature (no/limited clusters)
- Modified orientation increased:
 - Pre-spark heat release (PSHR)
 - LSPI; clusters of three and four events
 - $T_{\text{intake}} \geq 65^\circ\text{C}$ required

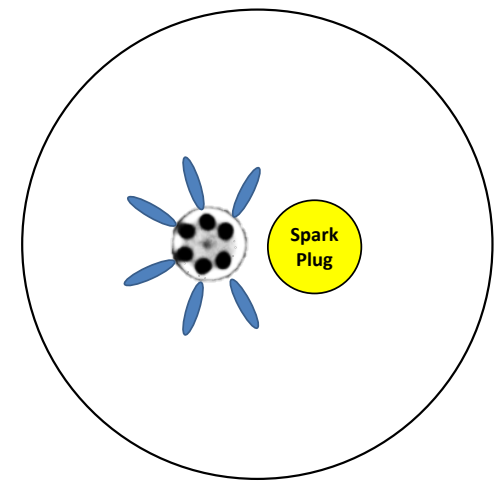
Neutron CT scan of injector tip



Stock Injector Orientation



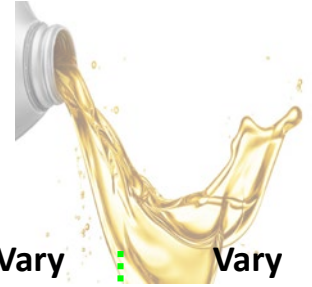
Modified Injector Orientation



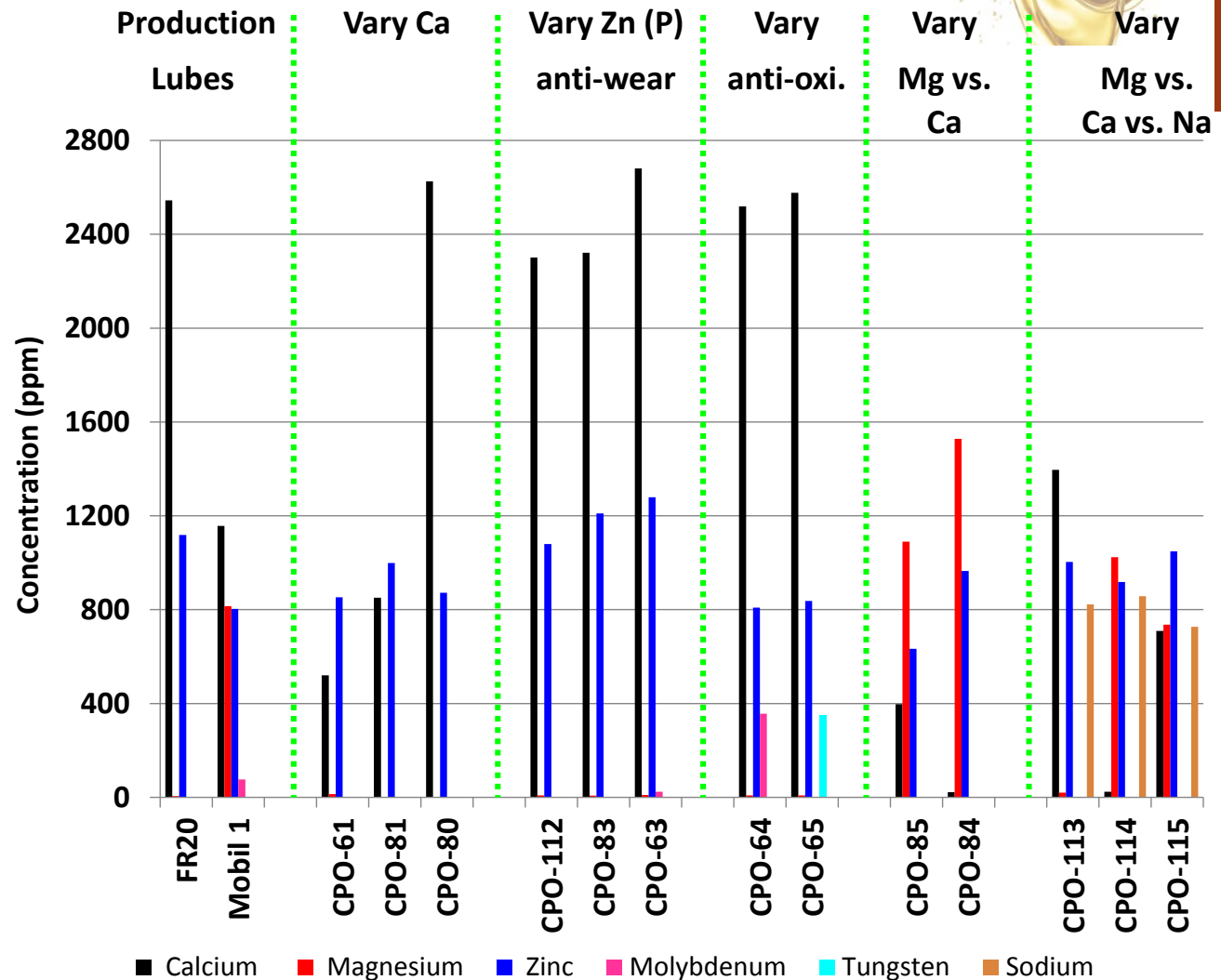
Hypothesis: Wall fuel/lube interaction increased ignition source and increased TDC reactivity increased ignitability

EXPLORING LSPI IN ENGINES

Additized Lubricants obtained for LSPI Experiments



- Partnering with **Driven Racing Oil** – Providing custom lubes
- Parametric variation of lubricant properties in common basestock
 - All lubes 5W-20, Group III (except Mobil 1)
 - Vary additive package in parametric manner
- Leverage Co-Optima effort with fuel effects
- **NREL** measured ignition delay
 - Same lubes, fresh and aged, evaluated in IQT



EXPLORING LSPI IN ENGINES

Lubricant mixture ignition kinetics support LSPI engine research

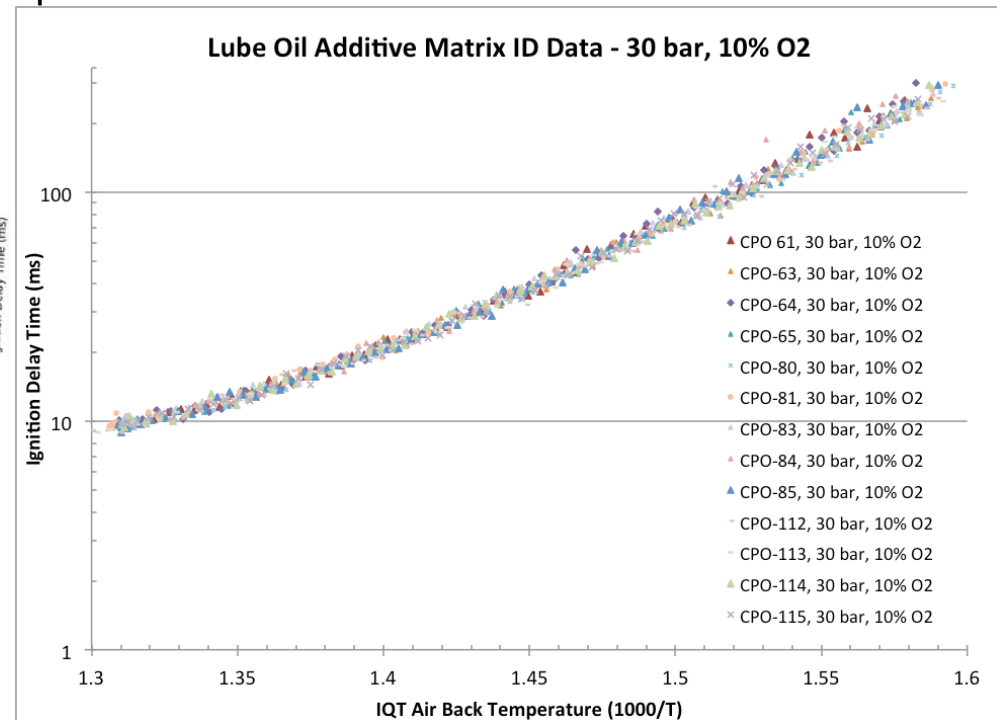
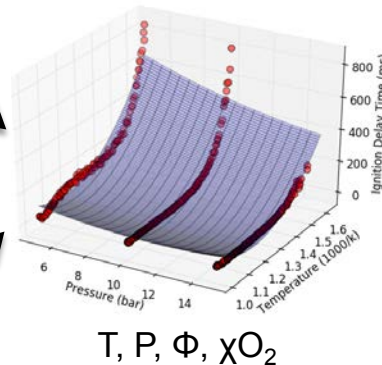
- **NREL** is conducting constant volume combustion chamber (CVCC) studies of ignition kinetics of lubricant / fuel surrogate blends under engine LSPI conditions.
- Differences in base lubricant chemistry have been identified
 - CVCC work to date has not isolated additive metal effects
 - Engine evaluations ongoing
- Experimental techniques are still under development to identify ignition behavior differences and tie to **ORNL's** LSPI engine experiments.



Ignition Quality Tester (IQT)



Advanced Fuel Ignition Delay Analyzer (AFIDA)



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“Energy Conserving” Lubricants are qualified on ASTM D7589 Sequence Test

- Lubricants compared to “ASTM Base Lube” (BL)
 - 20W-30 oil, provided to all Sequence test labs
 - GM V6 engine
- BSFC with test lubricant (TL) compared to BSFC with BL at six modal conditions after 16 and 100 hours of aging
 - Modal tests at relatively light load
 - Constant temperatures (115, 65, 35°C)
 - Weighted modes produce “Fuel Economy Improvement” (FEI) rating for fresh and aged oil
 - Typical test result: “2.0% FEI” = FEI1 + FEI2
- *No correlation to mpg, single engine result*

Objective

- Develop vehicle-based test protocol to bridge Sequence Test results to “real-world” mpg
- Investigate lubricant impact on FEI in broader scope (e.g., 4, 6, 8 cylinder, turbo GDI)



Designation: D7589 – 13

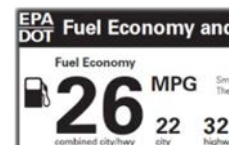
Standard Test Method for
Measurement of Effects of Automotive Engine Oils on Fuel
Economy of Passenger Cars and Light-Duty Trucks in
Sequence VID Spark Ignition Engine^{1,2}

This standard is issued under the fixed designation D7589; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last approval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

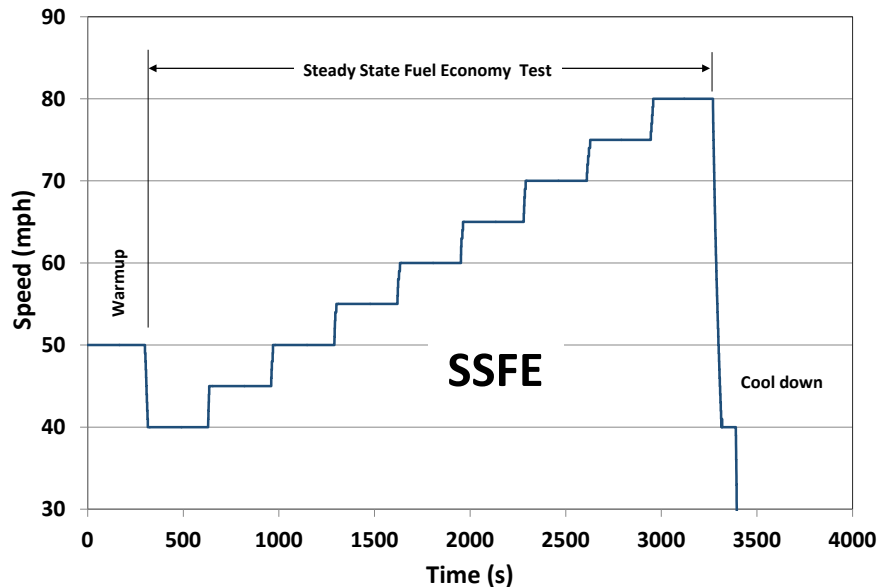
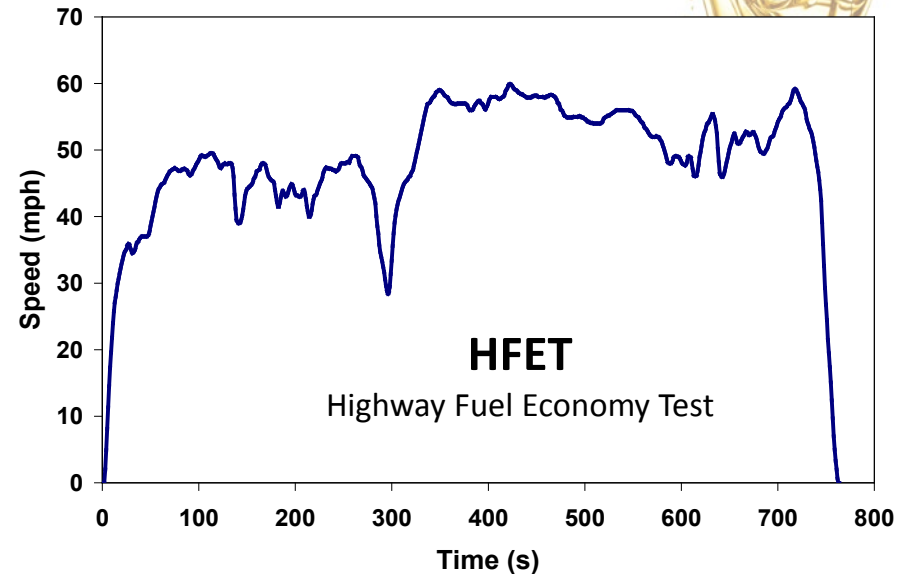
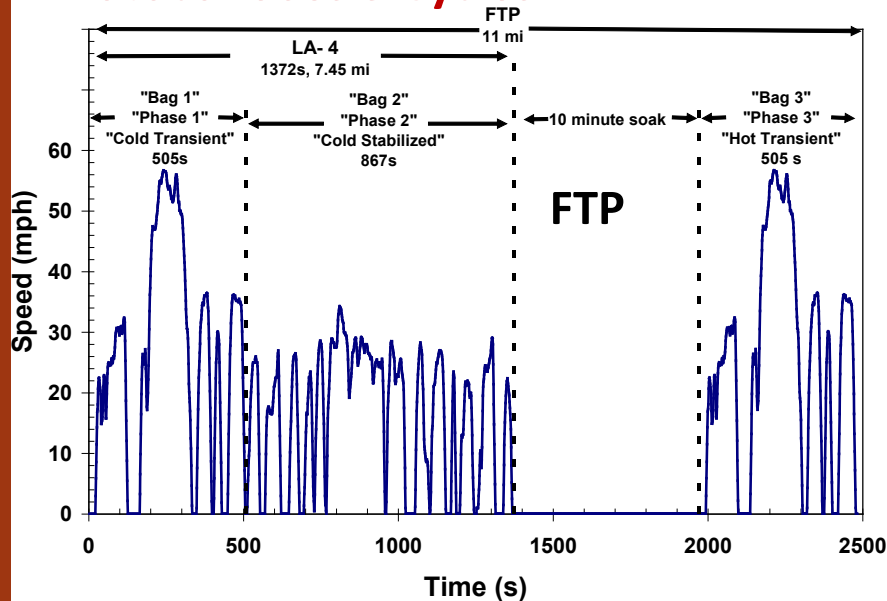
INTRODUCTION

This test method can be used by any properly equipped laboratory without outside assistance.

Can we apply different weighting to Seq Test modes to estimate vehicle fuel economy?



ORNL Vehicle Protocol Anchors all Test Lubes to ASTM Base Lube. Protocol Uses 3 Cycles:



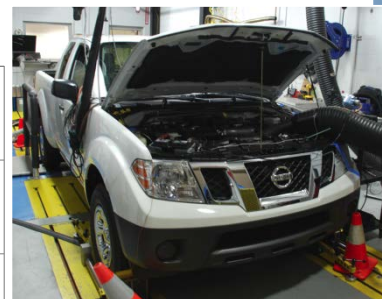
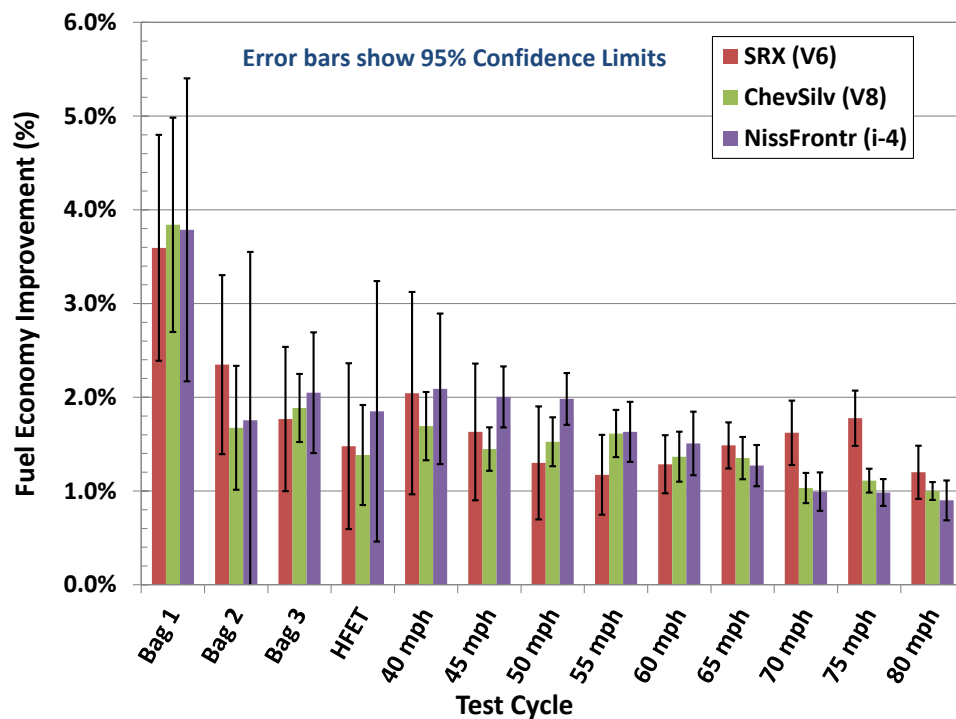
- **Federal Test Procedure (FTP), also known as City Cycle**
 - Includes "cold" start at 77°F (25C)
 - Used in emissions and fuel economy certification
- **HFET – Highway Fuel Economy Test**
 - Also for FE certification, warm engine
- **Steady State Fuel Economy Test**
 - Custom cycle, 5 min at each of 9 speeds

VEHICLE FUEL ECONOMY

TECHNICAL ACCOMPLISHMENT

Fuel Economy Improvements from <1% to >3% Measured in Vehicle Experiments Compared to ASTM Base Lube

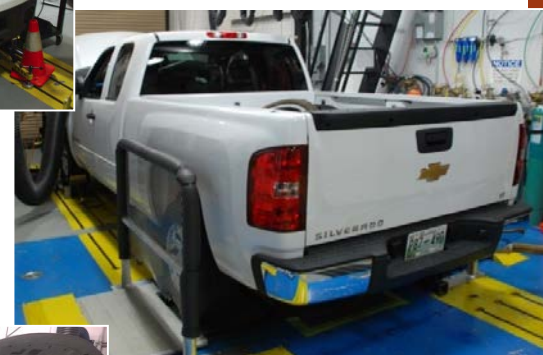
- Protocol includes City (FTP), Highway Fuel Economy Test (HFET), and Steady State Fuel Economy test (SSFE)
 - All Test Lubes anchored to ASTM Base Lube from Sequence VID/VIE (ASTM D7589)
- Completed 6 campaigns on 4 vehicles; *Statistically significant* FE improvements measured on multiple engines



Nissan Frontier i4



Cadillac SRX has same DOHC V6 engine used in Sequence VID test



Chevrolet Silverado V8 (Mobil1 and PNNL prototype)



BMW 320i Turbo GDI

2016 REVIEW - FT036 –LUBRICANT EFFECTS ON COMBUSTION, EMISSIONS, AND EFFICIENCY (ALSO FT014 – IMPACT ON EMISSION CONTROL CATALYSTS)

Three reviewers, Overall Score 3.6/4.0 (3.58/4.0)

Reviewer Comments All Favorable/Supportive

Approach and Technical Accomplishments

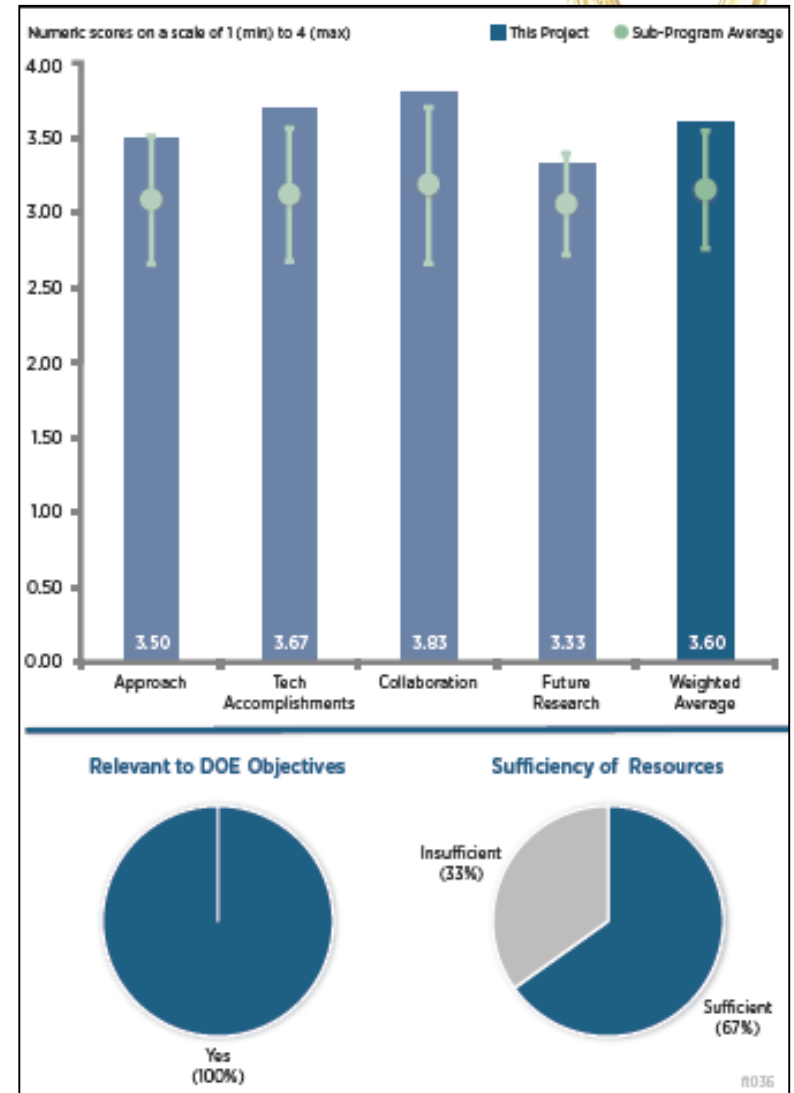
- “ ... investigative techniques ... excellent and unique...adequately address barriers”
- “adequate thus far...excellent results...excellent progress”

Collaborations

- “excellent collaboration and coordination...solid influence from industry collaborators”

Future work

- “well thought out plans...clearly defined...demonstrating how high VI gives more real world benefit would benefit community”
- “very relevant...fuel-lube interface not well understood... elucidate observed technical issues...lubricants can affect both future and legacy vehicles”



COLLABORATORS AND PARTNERS



- **Lubricant effects on PM formation in GDI engines:**
 - Ford – engine controller for start cart
- **Compatibility of Advanced Lubricants w/ Emissions Control**
 - Ford, Cummins, MECA, University of Tennessee
 - GM, Lubrizol
- **Exploring Low Speed Pre-Ignition in Engines:**
 - Driven Racing Oils – custom lubricants
 - Informal support from GM
- **Lube Effects on Vehicle Fuel Economy**
 - ASTM Test Monitoring Center – provide ASTM lubes
 - Biosynthetic Technologies, Inc.
- **2017 Lubricants Lab Call partners**
 - ANL, PNNL, NREL

REMAINING CHALLENGES

- Lubricant effects on PM formation in GDI engines

PM impacts of viscosity modifier and other additives for low viscosity lubricants

- Compatibility of Advanced Lubricants w/ Emissions Control

Identify negative impacts of lubricant additive metals on catalyst performance

- Exploring LSPI in Engines

Understanding Lubricant/Fuel Interactions critical to ameliorating LSPI

- Vehicle Fuel Economy

Map modal lube-derived Fuel Economy Improvement to multiple engines and drive cycles

PROPOSED FUTURE RESEARCH



Examine potential nanoparticle additives from Thrust I and II as well as commercial additives

Determine the impacts of boron-containing additives and new Thrust I and II materials

Quantify LSPI tendency with matrix of custom-blended lubes

Examine multiple lubes; bridge Sequence test results to vehicle level

Any proposed future work is subject to change based on funding levels

SUMMARY



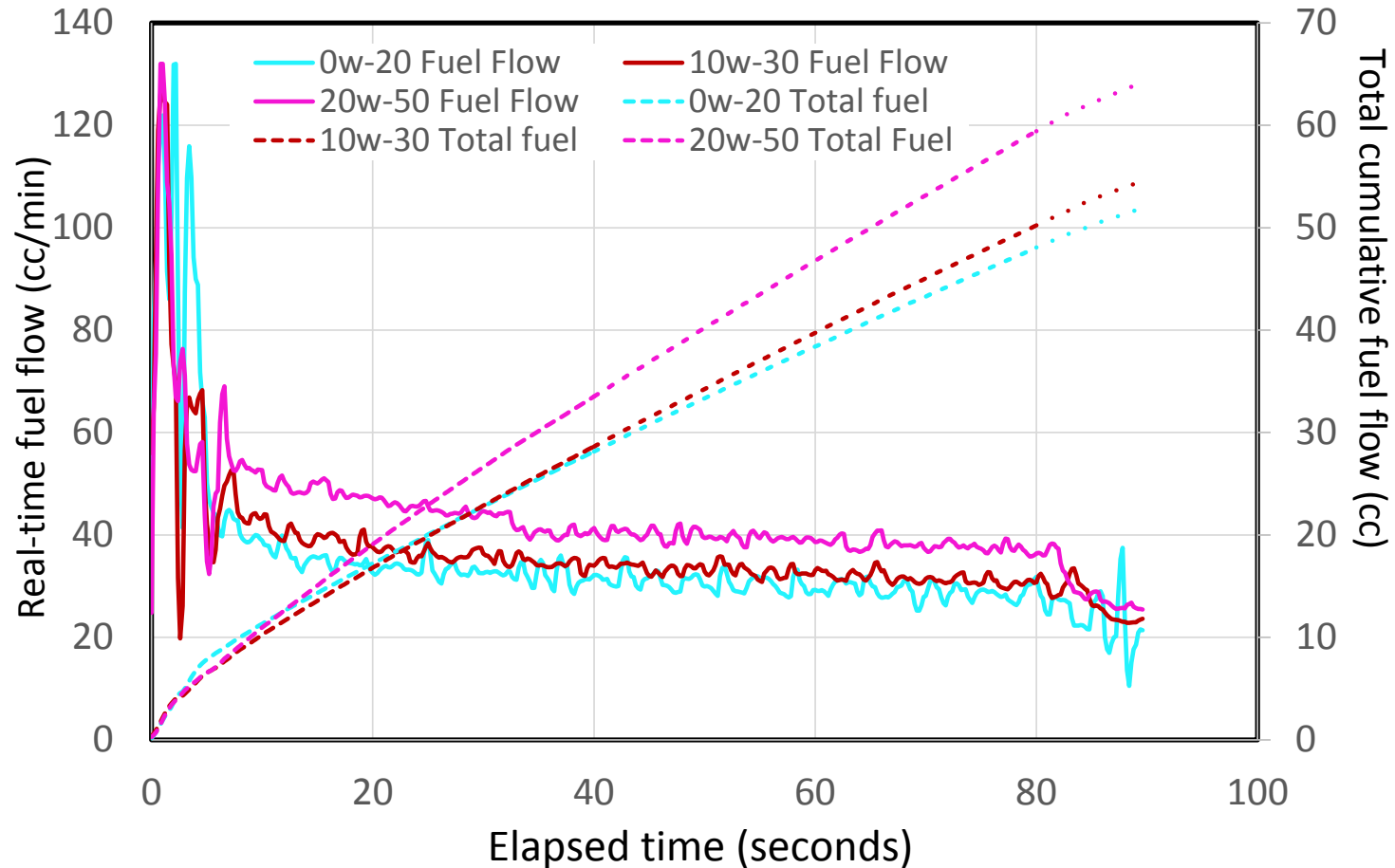
- **Relevance:** Studies provide understanding of impacts of lubricants on PM emissions, emissions control, engine LSPI, and vehicle fuel economy.
- **Approach:** Targeted engine, vehicle, and flow-reactor studies with in-depth characterization of PM, HCs, and fuel economy to better understand lubricant effects and interactions.
- **Collaborations:** Wide-ranging collaboration with industry, academia, and other national labs designed to maximize impact and lead to marketable solutions
- **Technical Accomplishments:**
 - Developed and employed engine-based test stands and vehicle tests to explore emissions, LSPI, and fuel economy impacts of lubricants
 - Completed experimental campaign with three different viscosities to identify lubricant contributions to PM during cold-start.
 - Compared impact of Ionic Liquid (IL) additive with ZDDP on 3-way catalyst
 - Developed engine protocol for reproducible LSPI event clusters
 - Established vehicle-based method to measure mpg improvement from lubricants
- **Future Work:** well-designed plans in place to address remaining barriers; guidance from industry incorporated into future directions

TECHNICAL BACKUP SLIDES

LUBRICANT EFFECTS ON PM FORMATION IN GDI ENGINES



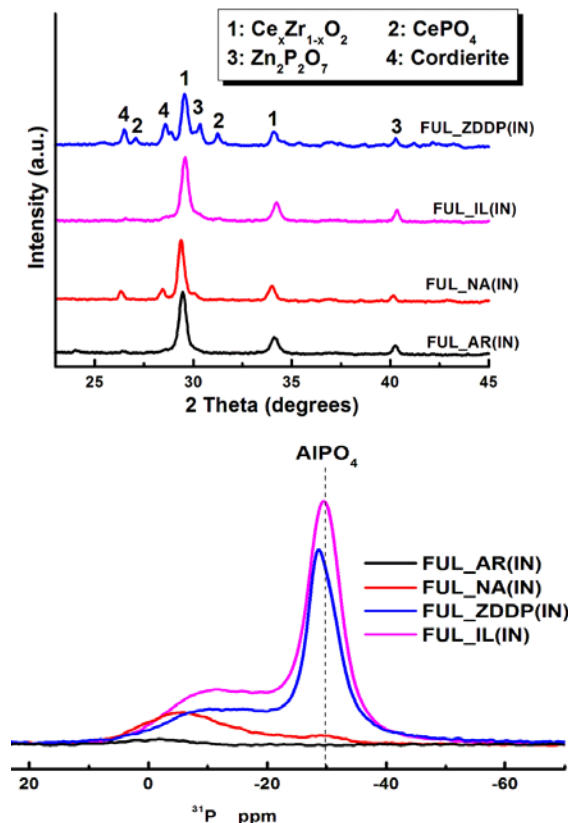
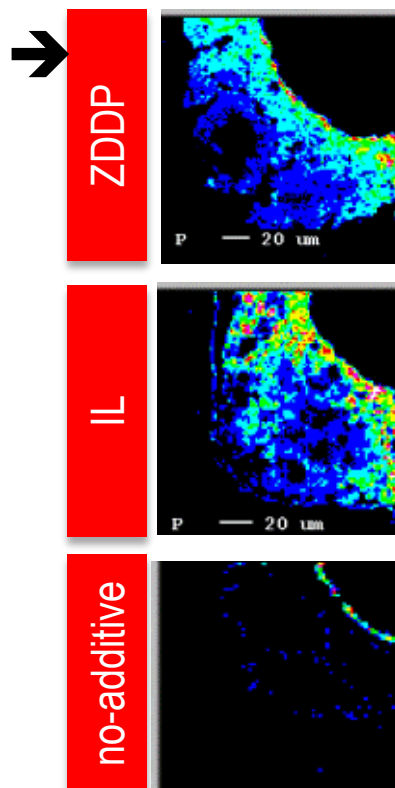
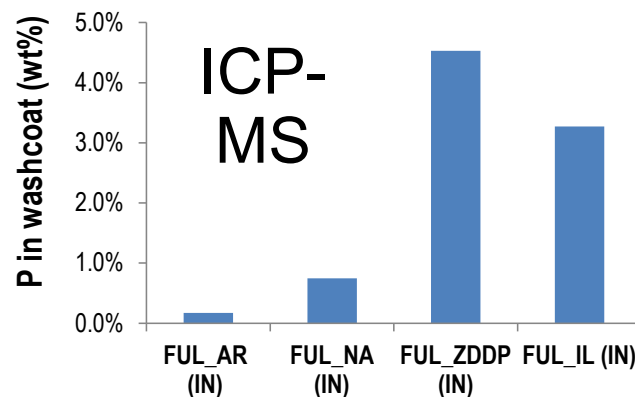
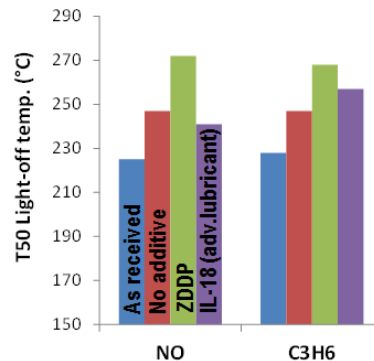
Fuel economy benefits of lower viscosity during cold start



- Fuel flow increases for higher viscosity oil – more work
- Extra spike for 0W-20 could indicate oil pressure compensation

IL-BASED P INTERACTS WITH TWC DIFFERENTLY THAN ZDDP-BASED P

- IL-aged TWCs consistently less-impacted than the TWCs aged with ZDDP
 - Light-off temperature, water-gas-shift reactivity and oxygen storage measured
- The ZDDP & IL-aged TWCs had significant Phosphorous (P), but the interactions with the TWC components were different
 - No observation of an overlayer with IL-aged samples
 - P more water soluble on the IL-aged TWC
 - Minimal formation of cerium phosphate with IL in XRD
 - With IL, formation of aluminum phosphate (AlPO_4), rather than ceria phosphate (CePO_4), appears to be the preferred form of P in TWC
 - Appears to lessen impact



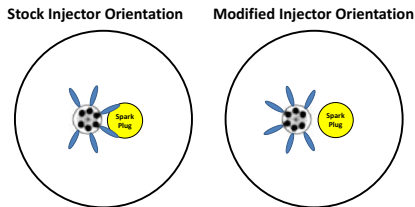
C. Xie et al., "Impact of Lubricant Additives on the Physicochemical Properties and Activity of Three Way Catalysts," Catalysts 6:4 (2016) 54.

EXPLORING LSPI IN ENGINES

Injector orientation influenced inhomogeneity and pre-spark heat release (PSHR)



- As $T_{\text{intake}} \uparrow$, PSHR indicates increased ignitability
 - More receptive to ignition from lube droplet

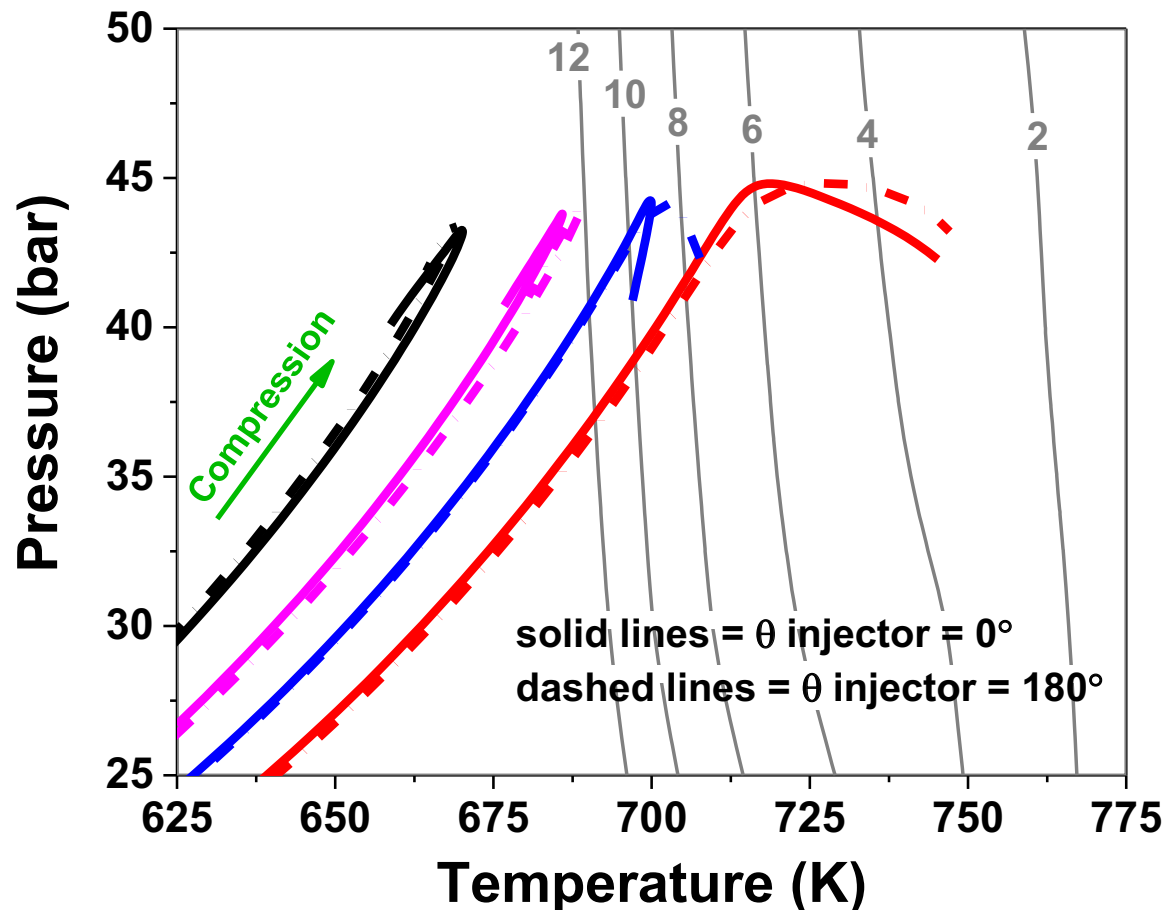


Conditions

- SOL timing retarded by 50°CA
- λ raised to 1.05
- Coolant Temp. lowered to ~68°C

$\Phi = 0.95$ calculated constant volume ignition delay time (ms)

$T_{\text{int.}} = 35^\circ \text{C}$ $T_{\text{int.}} = 50^\circ \text{C}$ $T_{\text{int.}} = 65^\circ \text{C}$ $T_{\text{int.}} = 80^\circ \text{C}$



Fuel Economy Improvement of Test Lube over Base Lube deemed statistically significant for majority of runs

Example: Chevrolet Silverado with Base Lube and Mobil 1



| FTP Bag 1 | | p value |
|-------------|--------|---------|
| BL1+BL2 | Mobil1 | 0.000 |
| BL1+BL2 | BLA | 0.484 |
| BL1+BL2+BLA | Mobil1 | 0.000 |

| FTP Bag 2 | | p value |
|-------------|--------|---------|
| BL1+BL2 | Mobil1 | 0.002 |
| BL1+BL2 | BLA | 0.373 |
| BL1+BL2+BLA | Mobil1 | 0.0003 |

| FTP Bag 3 | | p value |
|-------------|--------|---------|
| BL1+BL2 | Mobil1 | 0.000 |
| BL1+BL2 | BLA | 0.392 |
| BL1+BL2+BLA | Mobil1 | 0.000 |

| HFET | | p value |
|-------------|--------|---------|
| BL1+BL2 | Mobil1 | 0.000 |
| BL1+BL2 | BLA | 0.222 |
| BL1+BL2+BLA | Mobil1 | 0.000 |

- When $p < 0.05$, FE differences in lubes are statistically significant
- When $p > 0.05$, FE differences are not statistically different

Test Sequence:

BL1 → BL2 → Mobil1 → BLA

BL=Base Lube

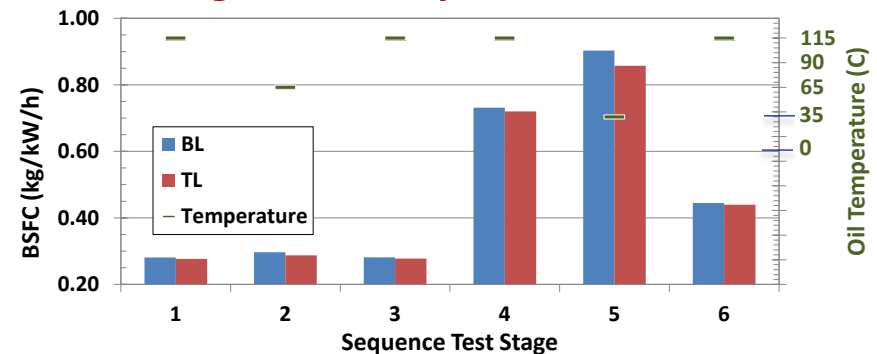
BLA=Base Lube After

Bridging vehicle Fuel Economy tests to Sequence tests:

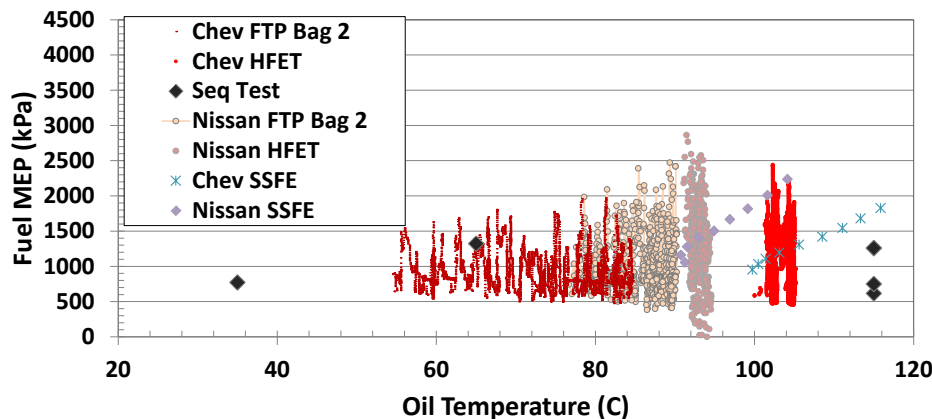
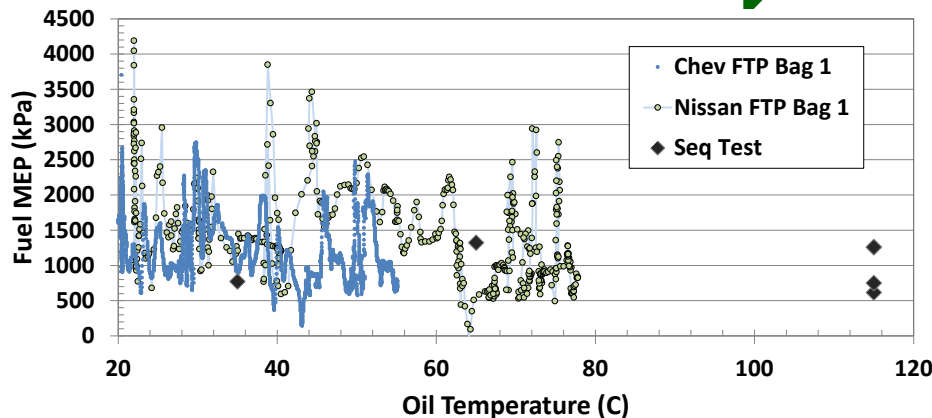
Fuel Mean Effective Pressure (Fuel MEP) normalizes fuel consumption to engine size and may be appropriate parameter to relate different engines to Seq test V6.



- Sequence test modes 1-3 under load at 2000, 1500 RPM. Modes 4-6 at idle
- Low BSFC (high efficiency) under load. Mode 6 has higher load, lower BSFC



$$\text{Fuel MEP} = \frac{\text{mass rate}_{\text{fuel}} * \text{LHV} * 2}{\text{Displacement} * \text{RPM}}$$



- Sequence test conducted at fixed oil temperatures
- Wide variation in oil temperature in transient vehicle operation
- FTP bag 1 starts at 20C, warms to ~50C in Chev V8, warms to >70C in Nissan 4cyl.

- FTP Bag 2, HFET, and SSFE tests show higher temps, closer to Seq Test 115C modes.
- Chevy warmer than Nissan on HFET and SSFE
- Nissan warmer than Chevy in Bag 2